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Influences of different contaminations on the electro-erosive and the electrochemical micro-machining

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Abstract

The machining processes EDM (Electric Discharge Machining) and ECM (Electrochemical Machining) are predestined for the micro machining and a high process accuracy of the removal processes. The high processing accuracy requires a very low working gap and leads to a high contamination through the removal process. The contamination leads to changes of gap conditions (process stability) which are explained by the electric field in the gap (EDM – electrostatic field and ECM – current density distribution). In the first part, the classification of contamination will be presented according to the state of aggregation and its residence time within the gap. These classifications enable to determine the contamination in predictable conditions or risk conditions, which provide the later selection of the special process regulations. In the second part, the contamination gas bubble for Micro-EDM and µPECMM (pulsed electrochemical micro machining) will be specifically investigated. The ignition conditions through the interaction of the gas bubble and conductive or non-conductive particles are analyzed for the micro-EDM. For the µPECMM, the gas formation in the areas gap-input and gap-output is analyzed in order to decide whether an open or closed gap system must be considered.

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Keywords: Micro machining, EDM, ECM, gap condtions

1. Introduction

The starting point of the observed non-conventional machining processes EDM and ECM is a liquid working fluid and electrode gap (working gap), which occur in the dimension of the contaminations.

The contaminations have their origin in the actual removal process and can impact positively or negatively on the process stability and the processing result. The primary selection is carried out on the basis of the state of aggregation of the contaminations [1], whereas a second classification can be provided according to the source of contamination (Fig. 1).

The most interesting contaminations are the gaseous species (type G, gas bubble - Fig. 2), because they have a large flexibility in origin and propagation inside and outside the working gap. In the paper, simulations and practical observations are presented, which show the changes in the electrical field conditions through gas bubbles and in conjunction with electrically-conductive and non-conductive particles.

2. Different classifications

2.1. Classification in closed, open and half-open systems

For the different applications and the better understanding of the contamination-effects in the work gap, the gap system must be divided in different categories. Fig. 1 shows the gap system with its internal contamination sources, the media output and input, the internal particle distribution, and the possible media-output outside the media cycle.
The first systems are the **closed systems,** in which the medium-circulation plays no role, and where the contamination density increases within the processing time T_c. After this time, the system must be opened (electrode oscillation) for a complete regeneration of the working gap. These periods, which reduce the processing efficiency to a large extent, are only acceptable, if quality (roughness, thermal layers) is the primary optimization factor. As for their application, these systems correspond to micro machining with gap widths smaller than 1 µm and wide processing areas,

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having large distances between the removal point and the edges of the inter-electrode gap.

The objective is to achieve an optimal distribution of the contamination, while only having a minimal impact on the process (no process instabilities).

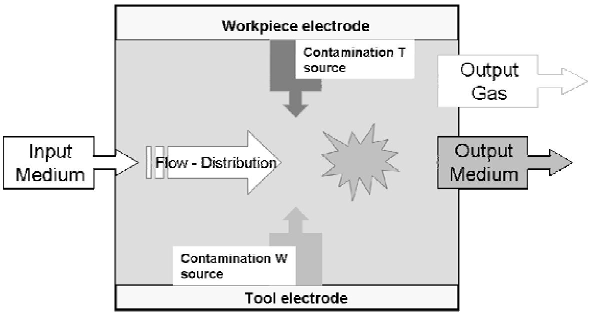

Fig. 1. Gap system for classification in closed or opened systems

In **open systems**, the distribution of contamination is mainly determined by the flow of the working medium. The contamination's density in the gap will be diluted for local sources (EDM), and transported outside the working gap. As regards the temporal average over several machining pulses, a low contamination of the gap can be expected. In case of distributed contamination (ECM) it has to be made sure that no flow-marks will occur and that the average contamination level is kept very low. The productivity will stay at a high level in both cases, while the bigger risk exists for the achieved machining-accuracy. In the application, these systems occur when small processing structures for larger workpieces are mapped. Also very simple gap-structures, where the flushing is done easily (laminar), can be based on an open system. These systems are only dependent on the used pulse energies and the pulse durations.

The **half-open systems** are very vague in their effect, i.e. they may act temporarily as closed or open systems. The flushing (medium-input and -output) does not work for the entire working volume, and the inner origins of contamination have the characteristics of closed local systems. A specific example is the µ-PECMM, where the non-insulated tool electrode generates gas out of the working gap and thus partially disturbs the medium-input- and -output-conditions (see 2.4). For this reason, type G represents a special contamination in this respect.

2.2. Classification according to state of aggregation

The classification according to the contamination's state of aggregation with different sub-selections is shown in Fig.2. The type S contamination (Fig. 2) represents solid removal particles which are the crystallized from the thermal effect, or were removed from the material composition. The latter can be recognized by their angular structure, while the thermal particles exhibit round surface structures. As for gap widths smaller than 1 µm, there is a great risk that these particles will block the working gap (non-conductive) or short-circuit it (electrically conductive). The size of the melting particles can be determined by the pulse energy/pulse duration, which is not possible for the fracture particles. Here, the particle size of the material to be processed plays the decisive role.

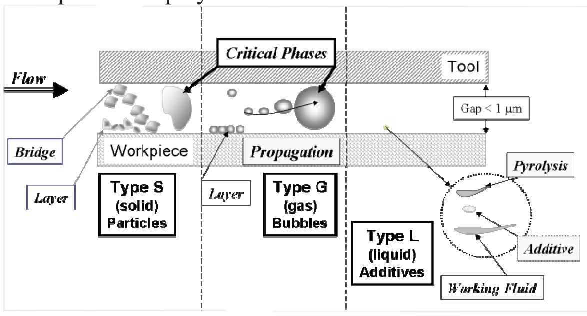

Fig. 2. Gap contaminations for micromachining [1]

Sludge is produced when applying the ECM, which consists of very small solid particles. The change of the current density distribution then depends on whether or not the sludge particles are electrically conductive.

The type G contamination is determined by the formation of gas in the working gap (Fig. 2). In case of spark erosion (EDM), the sources are the thermal effect of the discharge channel and a partial decomposition of the dielectric. For a short time, these effects work locally, but through the rapid succession of discharges the entire surface will be affected according to stochastic distribution.

The ECM has its sources of the gaseous contamination in the oxidation and reduction which primarily occur in the vicinity of the electrodes. These "area sources" exhibit differences due to the surface structure and the current density distribution in the electrolyte.

The gas parts, which dissolve in the working fluid or occur only briefly, are difficult to capture because they bond again very soon. On the other hand, gas layers may arise, which greatly alter the characteristics of the electrode surface, so that the removal process is completely interrupted. In case of the ECM, a passivation may occur which – partially or completely – will interrupt the process. The consequences are reduced erosion and a lower machining accuracy. As for the EDM, there is a risk that parts of the surface will be disadvantaged, leading to less discharges being allowed on average. These effects will particularly affect the processing accuracy.

Type-L contaminations are determined by the decomposition of the working fluid (pyrolysis) or through the use of additives. Regarding their dimensions, these contaminations are much smaller than the molecules of the working fluids (Fig. 2), and assume relevance primarily for the ignition behaviour (EDM) or chemical conversions (µ-PECMM).

3. Specification of the contamination – gas bubble

3.1. Influence of the flow of the working medium

In small working gaps (gap < 1 µm), a laminar flow of the working medium can be assumed [2], [3].

This means that the contamination problems arising at the electrode surfaces (ECM and partially EDM) are exposed to a low-oriented flow. This "braking effect" is reinforced by the roughness of the surface. Concerning the simulations of these G-contaminations, a rigid arrangement can therefore be assumed. The gap width is basically 1 µm, as defined in Fig. 2. The potential difference between the anode and the cathode is 100 V for the EDM and 0.1 to 4.0 V for the ECM.

3.2. Influence of the particle size for EDM and ECM

Fig. 3 shows the dependency of the field-factor in relation to the size of free electrically conductive contamination (EDM). In case of small G-contaminations on the electrode surface, the homogeneous field strength will be increased by 400% (local), while for particle sizes of approx. 80% of the gap width the field rise is more than ten times as high. The consequences for the EDM process are fast partial discharges towards the electrode and a fast collapse of the gas bubble.

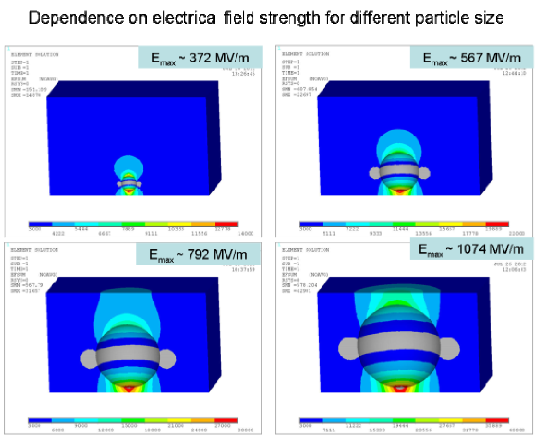

Fig. 3. Influence on the particle size (Micro-EDM)

In the µ-PECMM, the gas bubbles mostly stick to the electrodes (adhesion) and act as artificial "falsification" of the tool electrode. A decisive factor for the field distribution (flow field) is the modified characteristics of the working fluid, which has a low electrical conductivity. Fig. 4 schematically shows the possible distributions of higher and lower contamination and current density distribution. The simulation under simplified conditions already shows strong alterations concerning the current density distribution as well as machining inaccuracies resulting from that.

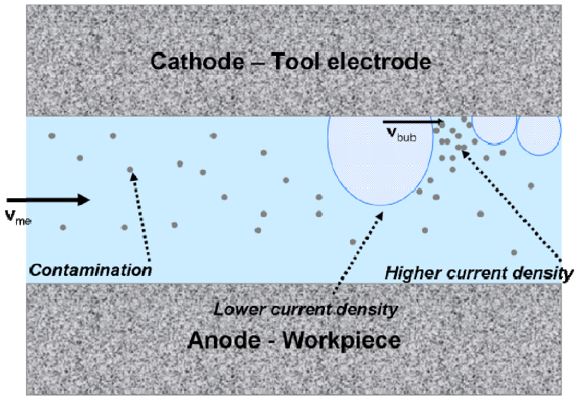

Fig. 4. Gap condition with different gas bubble (µ-PECMM)

Fig. 5 shows the simulation for a macro arrangement with different radii of gas bubbles; these results also apply to the micro machining, however. In open systems, where the flow rate (Fig. 4, v_{me}) is crucial, the polar current density increase can be reduced. An equally positive impact can cause the slight increase of the flow velocity between the gas bubble and the electrode. This power density distribution is only critical in closed systems.

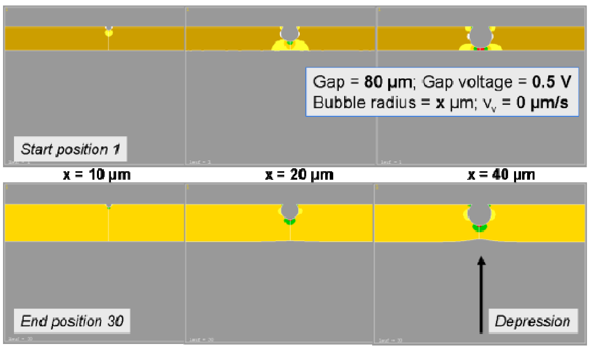

Fig. 5. Simulation for different gas bubble radii with a gap width of 80 µm [4]

3.3. Influence on particles in close proximity to the gas bubble for micro-EDM

3.3.1. Gas bubble or non-conductive particle

Taking the micro-EDM as an example will show how during the ignition phase (electrostatic field) the field conditions are changing. These changes will lead to additional forces effecting on the contamination, while also locally improved ignition conditions will occur, leading to partial discharges in the process. The crucial parameters of this simulation are the electrical field rise and the localization of this field extreme. The starting point of the reflections in Fig. 6 is the 3D-Simulation of two non-conductive spherical contaminations. Specifically, this can be a gas bubble or a conductive removal particle (oxides).

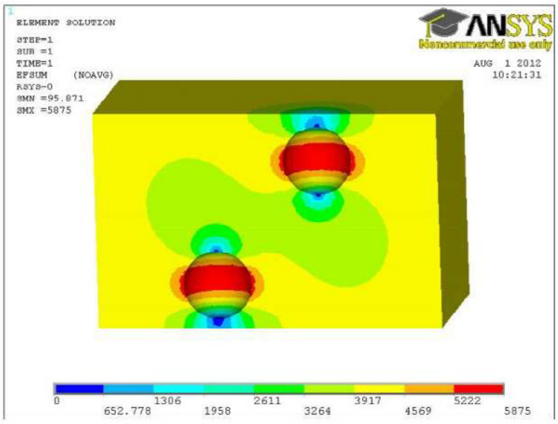

Fig. 6. Gas bubble (~ 0.25 µm) in the electrostatic field of the working gap (1 µm) – large distance

The gas bubbles are located in the area of low flow rates (laminar). The homogeneous electric field strength is 100 MV/m (Fig. 6, yellow area). Towards the electrode surfaces (gas bubble, polar) the field strength decreases strongly, i.e. there are no partial discharges towards the electrodes and no movement impulses towards the gap centre. The field factor in the equatorial area of the gas bubble can only lead to impulses between the gas bubbles in the same region. There is a field reduction to approximately 70% of the homogeneous field between the gas bubbles, i.e. the probability of partial discharges is very low.

In case of symmetrical arrangement of the gas bubbles (Fig. 7), the maximum electric field is reduced by only about 5 %. The probabilities that partial discharges will occur is limited to the direction of the gap flow. The assumption that the gas bubbles are not connected with the surfaces derives from the fact that there are only free gas bubbles in the gap after the collapse of the discharge load channel (plasma channel and surrounding gas bubble). The simulations assume distances between gas bubble and electrode surface of approximately 150 nm.

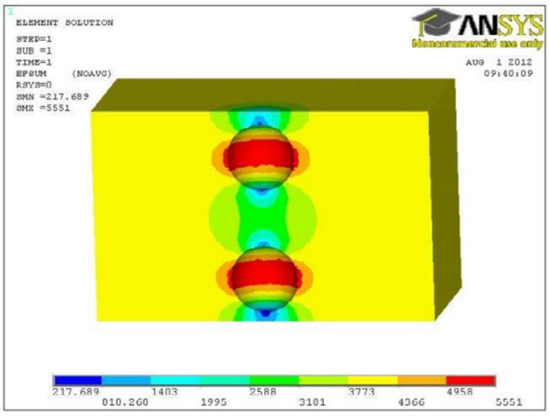

Fig. 7. Gas bubble (~ 0.25 µm) in the electrostatic field of the working gap (1 µm) – symmetric arrangement

3.3.2. Gas bubble and conductive particles

If the gas bubble approaches an electrode or an electrically conductive particle, then considerably higher field rises will occur (Fig. 8) and the gas bubbles receive an impulse towards the centre of the gap.

These field rises are polar on the spherical contaminations, i.e. the partial discharges occur in normal direction of the electrodes. In Fig. 8, this partial discharge (E_{max} ~ 400 MV/m) would occur towards the anodic tool electrode, while the area towards the work piece electrode is protected against partial discharges by the gas bubble.

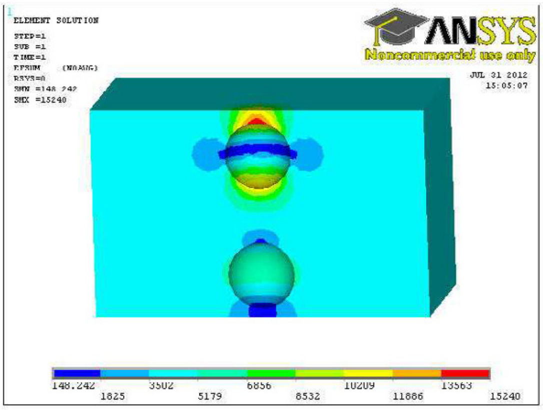

Fig. 8. Gas bubble (non-conductive) and particle (conductive) in the electrostatic field of the working gap (1 µm) – symmetric arrangement

The direct consequence of this arrangement is the movement of conductive particles in the middle of the gap and in the vicinity of the gas bubble (Fig. 9). The increased number of free electrically conductive particles in this gap section now improves the probability of ignition conditions.

These two polar positions are predestined for partial discharges through the central shifting of the conductive particle. The gas bubble (local area) defines only one region of the field dilution which is suited neither for partial discharges nor for complete ignitions.

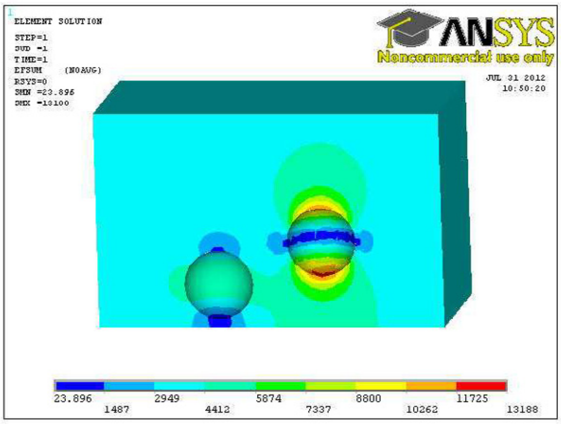

Fig. 9. Gas bubble (non-conductive) and particle (conductive) in the electrostatic field of the working gap (1 µm) – almost dislocated

3.3.3. Two conductive particles

Caused by the pulse movement of conductive particles, there can also be an encounter of two conductive particles. In this case, the field rise can be five to ten times as high as the homogeneous electric field strength.

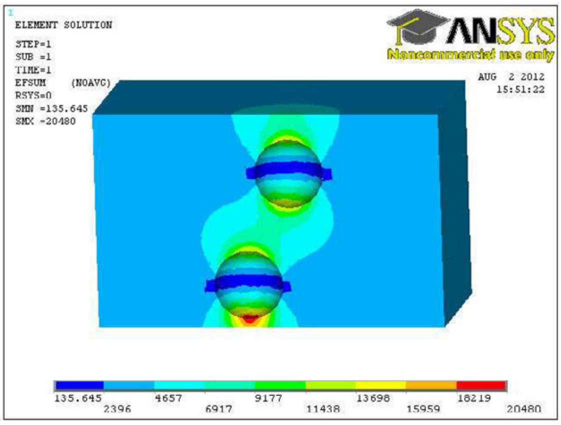

Fig. 10. Effect with two conductive particles – almost dislocated

The example of Fig. 10 shows the larger field rise between the lower electrode and the lower particle. But also in the upper area of the electrode the field rise is still almost three times as high. Between the particles, there is an area with a field rise from 2 to 3, i.e. the probability of a discharge in the gap is very large. It cannot be predicted, whether the partial discharges will lead to a streamer, or the existing streamers will already cause a main discharge.

To sum it up, all particle types in conjunction with a gas bubble lead to an acceleration of partial discharges. Essential for both conductive and non-conductive particles is the preferred direction of the partial discharge and the movement impulses generated by that.

3.4. Half-open system for µ-PECMM

The micro-ECM with very thin cone-shaped tool electrodes causes an initially open system to become a semi-open system. In Fig. 11 is shown that the gas formation is reinforced so much by the increase of the gap voltage that the flushing inputs and outputs are partially blocked. The conclusion drawn from that is very ambiguous, because in order to open the inputs/outputs higher gap voltages are necessary, while on the other hand the gap width and, therefore, the processing accuracy is determined by the gap voltage.

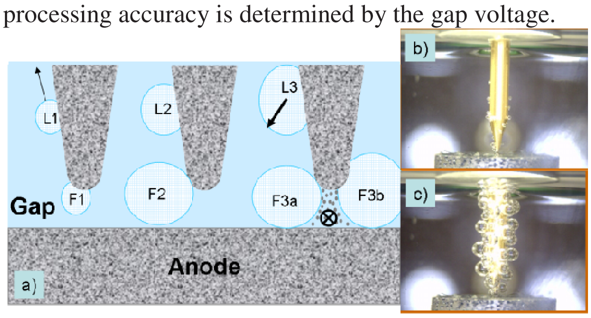

Fig. 11. Hydrogen reduction by µ-PECMM for different gap widths: (a) – schematic bubble blocking, b) gas bubble for gap voltage smaller 1 V, c) gas bubble for gap voltage higher 3 V).

A second very important effect is the "isolation" of the free tool electrode. This way, the complete current density is concentrated on the workspace.

The effect of a higher current density in the working gap results in a higher removal, but also influences the processing quality. The "isolation" into lateral gaps can also lead to the complete blockade of flushing, which is not desirable. The removal of this passive layer can be achieved by reversing or controlled EC-pulses (pulse energy/pulse duration). In this processing arrangement, a continuous flushing mechanism must be maintained, so that the high processing accuracy of micro machining can be ensured.

The "conical" tool electrode and the arrangement of the gas bubbles provide that the gas bubbles will collapse earlier and will not block the gap as in Fig.11a (3). The maximum electric field strength is determined by the geometry of the electrode, the distribution of the gas bubbles and the surface roughness.

Basically, the gas bubble influences in the μ-PECMM are more critical than for the spark erosion, because due to the discharge distribution critical areas can be temporarily ruled out for the local removal of the EDM. The electrical and thermal breakthroughs of electrolytes in the μ-PECMM are a very problematic case in this respect.

4. Conclusion

The influence of contaminations is the main cause for changed gap conditions and process instabilities, which applies both for the machining micro-EDM and the μ PECMM.

The contaminations cause a reduction in gap space and above all a change of the electric field in the gap. The work times of the electric fields are different in this respect, i.e. for the micro-EDM it is the electrostatic field during the ignition phase (pulse pause), and for the μ-PECMM it is the electric flow field during the removal phase (pulse duration).

In order to minimize the influences of the field inhomogeneities, they first have to be localized and their rise determined.

In case of the micro-EDM, this will change the breakdown probability, i.e. the electric field strength may rise up to a certain factor. However, it will only be critical if the working gap cannot be regenerated quickly enough.

For the μ-PECMM, the rise of the current density leads to higher removal rates, possibly up to the trans-passive machining range.

Other differences include non-conductive gas bubbles or conductive removal particles, which for the micro-EDM can be effective in a dielectric. The particles can locally increase the electrostatic field up to a factor of 10. For non-conductive particles including gas bubbles, this field rise is between 1.5 and 3. As a result, smaller ignition voltages can be used to allow higher machining accuracy.

For the μ-PECMM, the increases in the field inhomogeneities are lower, because the work is done in an electrolyte. In addition to the positive effect of improving the removal, there are also critical situations to be noticed, e.g. electrical discharges or very strong changes of the electrical conductivity due to increased removal-contamination.

Simulations allow for a good assessment of the field changes, so that critical limits for the process control systems can be defined. The next step is then to create easily controllable process energy sources by using these limits, which counter the negative effects, but take maximum advantage of the positive effects. This balance lies in a very narrow parameter area, which in turn may differ a lot for the various materials.

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